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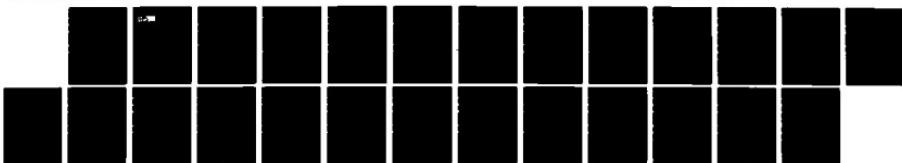
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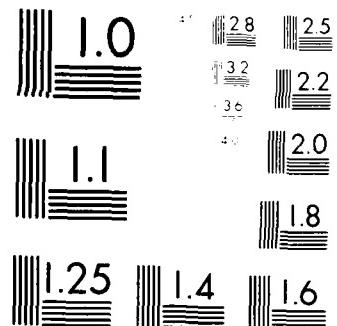
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AFOSR-TR-86-8498 F49628-83-C-0061

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AD-A170 244

PD-NW-86-3432

NONLINEAR INTERNAL GRAVITY WAVE PROPAGATION, SATURATION, AND ABSORPTION  
IN THE ATMOSPHERE

Timothy J. Dunkerton  
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9 April 1986

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Final Report  
Contracts #F49620-83-C-0061  
#F49620-85-C-0032

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Prepared for  
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## REPORT DOCUMENTATION PAGE

Form Approved  
OMB No. 0704-0188  
Exp. Date: Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION <b>UNCLASSIFIED</b>		1b. RESTRICTIVE MARKINGS <b>NONE</b>													
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION/AVAILABILITY OF REPORT <b>Approved for public release, distribution unlimited</b>													
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE															
4. PERFORMING ORGANIZATION REPORT NUMBER(S)  <b>PD-NW-86-343R</b>		5. MONITORING ORGANIZATION REPORT NUMBER(S)  <b>AFOSR-TR- 86 - 0490</b>													
6a. NAME OF PERFORMING ORGANIZATION  <b>Physical Dynamics, Inc.</b>	6b. OFFICE SYMBOL (if applicable)  <b>NC</b>	7a. NAME OF MONITORING ORGANIZATION  <b>Air Force Office of Scientific Research</b>													
6c. ADDRESS (City, State, and ZIP Code)  <b>300 120th Ave NE, Bldg. 7, Suite 220 Bellevue, WA 98005</b>		7b. ADDRESS (City, State, and ZIP Code)  <b>Bolling AFB Washington, DC 20332</b>													
8a. NAME OF FUNDING/SPONSORING ORGANIZATION  <b>AFOSR</b>	8b. OFFICE SYMBOL (if applicable)  <b>NC</b>	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER  <b>F49620-83-C-0061 and F49620-85-C-0032</b>													
8c. ADDRESS (City, State, and ZIP Code)  <b>Bolling AFB Washington, DC 20332</b>		10. SOURCE OF FUNDING NUMBERS  <table border="1"><tr><td>PROGRAM ELEMENT NO.  <b>6110.2F</b></td><td>PROJECT NO.  <b>4310</b></td><td>TASK NO.  <b>H1</b></td><td>WORK UNIT ACCESSION NO.</td></tr></table>		PROGRAM ELEMENT NO.  <b>6110.2F</b>	PROJECT NO.  <b>4310</b>	TASK NO.  <b>H1</b>	WORK UNIT ACCESSION NO.								
PROGRAM ELEMENT NO.  <b>6110.2F</b>	PROJECT NO.  <b>4310</b>	TASK NO.  <b>H1</b>	WORK UNIT ACCESSION NO.												
11. TITLE (Include Security Classification)  <b>Nonlinear Internal Gravity Wave Propagation, Saturation, and Absorption in the Atmosphere</b>															
12. PERSONAL AUTHOR(S)  <b>Timothy J. Dunkerton</b>															
13a. TYPE OF REPORT  <b>Final</b>	13b. TIME COVERED  <b>FROM 2/10/83 TO 2/9/86</b>	14 DATE OF REPORT (Year, Month, Day)  <b>1983 April 9 1986</b>	15 PAGE COUNT  <b>19</b>												
16. SUPPLEMENTARY NOTATION															
17. COSATI CODES  <table border="1"><tr><th>FIELD</th><th>GROUP</th><th>SUB-GROUP</th></tr><tr><td></td><td></td><td></td></tr><tr><td></td><td></td><td></td></tr><tr><td></td><td></td><td></td></tr></table>	FIELD	GROUP	SUB-GROUP										18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)  <b>internal gravity waves, critical layers</b>		
FIELD	GROUP	SUB-GROUP													
19. ABSTRACT (Continue on reverse if necessary and identify by block number)  <p>Numerical and theoretical studies of internal gravity waves have been performed to understand the role of convective instabilities in nonlinear, large-amplitude gravity waves; the effects of saturation and self-acceleration on transient gravity wave, mean-flow interaction; the role of local convective instabilities in producing turbulent modifications of potential temperature and trace constituents in breaking gravity waves; and the propagation and refraction of inertial and non-inertial gravity waves through observed middle atmosphere wind fields. Simulations with a two-dimensional, nonhydrostatic gravity wave model indicate that convective adjustment in unstable gravity waves results in a mean flow modification closely approximated by WKB saturation theory in cases where the incident wave field is nearly monochromatic. Convection also limits, and practically prevents, the evolution to a reflecting nonlinear critical layer, even when the incident wave field is not monochromatic. Some critical layer dislocation is observed due to self-acceleration in transient gravity waves. Localization of turbulence in a convectively unstable gravity wave can greatly reduce</p>															
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS		21. ABSTRACT SECURITY CLASSIFICATION  <b>UNCLASSIFIED</b>													
22a. NAME OF RESPONSIBLE INDIVIDUAL		22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL												

19. ABSTRACT (continued).

the mixing of heat and trace constituents and implies a large turbulent Prandtl number. Significant lateral movement and refraction of gravity wave rays is observed for inertia-gravity waves in realistic wintertime flows. A formula is derived for the onset of dynamical instability in inertia-gravity waves, having a lower threshold than the corresponding amplitude required for convective instability.

PD-NW-86-343R

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Final Report  
Contracts #F49620-83-C-0061  
#F49620-85-C-0032

Prepared for  
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH  
Bolling AFB  
Washington, DC 20332

JUL 28 1986

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## 1. INTRODUCTION

Internal gravity waves are a ubiquitous feature of the terrestrial atmosphere. These oscillations arise from the restoring forces due to the stable stratification of the troposphere, stratosphere, and mesosphere. Due to decreases of ambient density with height, these waves have a natural tendency to grow with height. It is well known, of course, that such an amplification process cannot continue indefinitely. At some point, the displacement of local isentropic surfaces by the internal wave field becomes sufficiently great that these surfaces overturn and become convectively unstable. We then have a locally unstable flow within the wave field, even though the ambient field is statically stable. As a result, the wave field breaks down in the form of local convective instability.

The immediate implications of the breakdown are two-fold. First, up to the point of convective breakdown the internal gravity wave has been transporting momentum vertically in such a manner that the Eliassen-Palm theorem is satisfied. That is to say, for simple two-dimensional waves the vertical momentum flux is constant in height, provided that the waves are steady and conservative. However, once convective instability breaks out, the flow can no longer be considered as steady and conservative, in the sense that parcel displacements are no longer reversible, but irreversible, due to convective turbulence. Thus, the momentum flux, previously constant with height (and therefore having identically zero effect on the mean flow), now decays with height in the unstable region and decelerates the mean flow in the direction of the wave phase speed.

Second, the irreversible mixing of heat and trace constituents begins to occur within the unstable region. Prior to breakdown, parcel displacement fields were exactly reversible, under the assumption of conservative motion, and no net tracer transport would have occurred. After breakdown, the mean heat and tracer fields begin to undergo irreversible mixing.

Momentum deposition and constituent mixing are therefore the two major effects of breaking gravity waves. It is well known that this process is of primary importance in the mesosphere (Lindzen, 1981). However, it could also be argued that a related process is of importance in the upper troposphere and lower stratosphere due to breaking inertia-gravity waves (Dunkerton, 1984), and indeed may be of importance at all levels of the middle atmosphere in winter (Fritts *et al*, 1986).

The purpose of the research funded by the Air Force Office of Scientific Research under Contracts F49620-83-C-0061 and F49620-85-C-0032 has been to investigate, both theoretically and numerically, the role and nature of internal gravity wave propagation, breakdown, and absorption in the terrestrial middle atmosphere. Specific objectives of the work are now described.

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## 2. OBJECTIVES OF THE RESEARCH EFFORT

The complete list of the objectives of the research effort is as follows:

a. Role of convective instability in nonlinear, large-amplitude internal gravity waves

The purpose of this objective is to determine, with the help of a two-dimensional numerical model of stratified shear flow, how a large-amplitude gravity wave incident on its critical layer undergoes absorption and subsequent mean flow modification due to convective breakdown. It was proposed to test the semi-analytic WKB theory of Dunkerton (1982) with the numerical code of Fritts (1982). The semi-analytic theory is a quasi-linear WKB theory describing, within the context of these two approximations, how a monochromatic gravity wave evolves as it propagates through a slowly-varying mean flow, possibly toward its critical layer. In this objective we sought to determine the wave action evolution, mean flow modification, and turbulent diffusion due to the wave amplification as the critical layer is approached. Wave amplification is also caused by the decrease in ambient density with height.

b. Effects of saturation and self-acceleration on transient gravity wave, mean-flow interaction

The purpose of this objective is to determine, with the help of a two-dimensional numerical model, what are the "self-acceleration" effects of the mean flow modification on the primary incident wave field. This effect was

also included in Dunkerton's semi-analytic model by Coy (1983) and had several interesting theoretical implications. First, the transience of the mean flow, due directly to the transience and breakdown of the wave, brings about a change in the phase speed of this wave due to wavenumber conservation. Second, the self-acceleration mechanism would imply that the mean flow deceleration would not be limited by the initial phase speed of the incident wave, but rather would evolve to some undetermined value well beyond this point. Such a mechanism could, of course, have quite profound consequences as to how we view the effects of such waves on the terrestrial mesosphere and lower thermosphere. Third, a primary wave incident on a critical layer could dislocate the level of this layer to some undetermined higher level, implying a greater depth of mean flow modification and mixing than would be the case without self-acceleration.

#### c. Role of convective instabilities in heat and constituent transport

The purpose of this objective is to determine the evolution of heat and constituent transport in a monochromatic gravity wave field when the primary wave becomes large enough to overturn and undergo local convective instability. Specifically, we need to inquire as to what are the effects of such local mixing relative to the background stratification of potential temperature and constituents. The problem is of interest for a simple reason: the mixing that is occurring due to convective instability within the wave field is acting in a locally downgradient manner to stabilize the flow locally. Insofar as the local flow is statically unstable, the turbulent fluxes of heat and trace constituents are going to be downgradient relative to the local (unstable) stratification, and hence countergradient relative to

the ambient stratification. Hence, the net mixing of heat and trace constituents by the breaking internal wave may be substantially less than, or even the opposite, of that implied by Lindzen's (1981) turbulent diffusion parameterization.

d. Propagation and refraction of inertial and non-inertial gravity waves in observed wintertime flows

The purpose of this objective is to utilize the observed wintertime flow in the middle atmosphere, consisting of a zonally averaged flow and several of the gravest zonal planetary wave harmonics, to investigate the lateral propagation and refraction of gravity waves on their way to the mesosphere. The problem is of importance because the planetary waves are frequently of large amplitude in winter, and therefore the zonally-averaged flow can no longer be used to infer anything about internal gravity wave propagation. More broadly, the lateral propagation and refraction are two effects that must necessarily be taken into account when interpreting observations of gravity waves. For example, the presence of gravity waves in the mesosphere over a specific station (e.g. Urbana) could be indicative of gravity wave excitation at some distant location (e.g. Colorado Rockies). The orientation of the wave would also be modified by *in-situ* lateral shear of the flow.

### 3. ACCOMPLISHMENTS OF THE RESEARCH EFFORT

#### a. Numerical studies of unstable wave, mean-flow interaction

A complete description of these studies is provided in Dunkerton and Fritts (1984). In that paper, simulations of two-dimensional, nonhydrostatic, noninertial waves were performed. These model studies demonstrated that convective adjustment with the locally unstable wave field would act to modify the mean flow in a manner quite similar, if not identical, to the convective adjustment parameterization advanced by Lindzen (1981) and examined theoretically in some detail by Dunkerton (1982). In cases where a nearly monochromatic wave is incident on its critical layer--the case addressed by our semianalytic theory--the mean flow modification is primarily restricted to the layer beneath the critical level (insofar as self-acceleration is unimportant) and acts to create a mean flow ledge underneath this level. On the other hand, simulations of non-monochromatic or highly transient gravity waves indicated the expected poor agreement with the WKB semi-analytic theory. In this case the mean flow modification occurred over a broad range of levels centered about the critical level, and no ledge was observed to form. Another departure from WKB theory is found when partial reflection from the ledge is observed to occur due to steep mean flow shears there.

Convection-induced turbulence, parameterized in the form of convective adjustment, also limits, and practically prevents, the evolution to a reflecting nonlinear gravity wave critical layer.

b. Saturation and self-acceleration due to ambient density effects

A complete description of this work is given in Fritts and Dunkerton (1984). In this study, we investigated the evolution and breakdown of internal gravity waves propagating over a much deeper vertical domain than in Dunkerton and Fritts (1984). In such a domain, the primary wave undergoes growth due to decrease in ambient density, rather than incidence on a critical layer. According to Coy (1983) we expect self-acceleration to be much more important in this case.

Such was found by Fritts and Dunkerton (1984), and the agreement with the semianalytic theory was again excellent in monochromatic wave cases. We then proceeded to determine how such a self-accelerated wave would interact with its critical layer at the top of this domain. It was of interest to determine whether the wave would undergo absorption as if its initial critical level were still relevant, or whether the wave, now having a different phase speed within the center of the wave packet, would propagate through the initial critical level to some new, self-accelerated critical level.

First, the semi-analytic theory was carefully inspected to determine whether a self-accelerated wave incident on a critical level would dislocate this level to some higher level. The answer was apparently "no," because the self-acceleration was automatically zero at the front of the wave packet, and no mean flow acceleration would have occurred at this point. Therefore the front of the wave packet continued to possess its initial value of phase speed and could not then penetrate the initial critical level.

Next, the numerical model was used to investigate the same question.

This model does not depend on the WKB approximation. In this case, some critical layer dislocation was observed, contrary to the semi-analytic model. The reason seemed to lie in the inevitable, though small, violation of WKB theory due to the transient or impulsive excitation of the wave packet. This excitation produces a narrow band of frequencies, each of which contributes to the mean flow acceleration, and hence are each affected by self-acceleration. Thus we observed a kind of cooperation between spectral broadening and self-acceleration, producing critical layer dislocation even though the semi-analytic theory did not seem to anticipate this effect.

c. Fluxes of heat and trace constituents in convectively unstable gravity waves

The complete description of this study is given in Fritts and Dunkerton (1985). In that paper, an expression was derived for the effective turbulent diffusion of heat and constituents (not momentum) due to convectively unstable monochromatic internal gravity waves. The ratio of this diffusivity to the turbulent eddy viscosity, i.e. the turbulent Prandtl number, was found to depend on the amplitude of the wave and the degree of localization of convective turbulence within the wave field. Global turbulence, nearly uniform through the wave field, would produce downgradient mixing, whereas very localized turbulence, within the convectively unstable zone only, would produce net countergradient mixing. For realistic amplitudes and degree of localization, the net mixing could be extremely small or zero. Although this result was derived for monochromatic waves, a similar line of thinking would apply equally well to a superposition of waves. The basic restriction is that we consider convective turbulence only, and that other sources of turbulence,

such as dynamical or KH instability, are not present. Mixing due to KH waves will be downgradient relative to the ambient stratification.

d. Ray tracing in realistic wintertime flows

These studies were described by Dunkerton and Butchart (1984) and Dunkerton (1984). We used some observed mean flow and planetary wave fields in the stratosphere to infer the lateral propagation and horizontal refraction of noninertial and inertia-gravity waves, respectively, in these two papers. The basic conclusion of these studies is that lateral propagation and horizontal refraction can be safely ignored for the smaller-scale gravity waves of horizontal wavelength less than about 200 km, whereas these two effects cannot be ignored for much longer waves. (This is a general statement and cannot be taken absolutely; circumstances can be found when small-scale waves are refracted horizontally, as near the critical level. However, in this case, wavebreaking and absorption are usually going to occur.)

By examining the vertical propagation through a basic state distorted by a major sudden stratospheric warming, we found that zones of propagation existed in regions where the flow was westerly, as around the southern periphery of the displaced (or divided) circumpolar vortex. Therefore sudden warmings do not even come close to eliminating the vertical propagation of gravity waves to the mesosphere.

An expression was also derived for the dynamical saturation of inertia-gravity waves due to dynamical or KH instability. Such a mechanism is operative in the region of negative vertical shear above the tropospheric jet streams, consistent with observations of local turbulence layers within inertia-gravity waves (Barat, 1983).

#### 4. LIST OF PUBLICATIONS ARISING FROM THIS WORK

"Inertia-gravity waves in the stratosphere," T.J. Dunkerton, J. Atmos. Sci., 41, 3396 (1984).

"Transient gravity wave-critical layer interaction, Part I: Convective adjustment and the mean flow acceleration," T.J. Dunkerton and D.C. Fritts, J. Atmos. Sci., 41, 992, (1984).

"A quasi-linear study of gravity-wave saturation and self-acceleration," D.C. Fritts and T.J. Dunkerton, J. Atmos. Sci., 41, 3272 (1984).

"Fluxes of heat and constituents due to convectively unstable gravity waves," D.C. Fritts and T.J. Dunkerton, J. Atmos. Sci., 42, 549 (1985).

## 5. CONCLUSIONS AND RECOMMENDATIONS

A semi-analytic theory of gravity wave, mean-flow interaction was proposed several years ago by Dunkerton (1982). The present study has tested the predictions of this theory with a two-dimensional numerical model of nonhydrostatic, noninertial gravity waves, and applied it to case studies of gravity wave propagation in realistic wintertime flows. Excellent agreement with the theory was found--particularly concerning momentum transport--both in cases where a primary wave was incident on its critical level and where the wave underwent self-acceleration due to ambient density decrease. One surprising result we discovered was that the mixing of heat and constituents by the localized convective turbulence within the unstable wave field would act to reduce the net mixing of the background stratification. In summary, the present study serves to motivate a straightforward application of the semi-analytic theory to the observed flows of the middle atmosphere, using the spatial and seasonal variations that would affect gravity wave propagation. A preliminary study of this sort has been done here; henceforth, the method can be used by the observer as well as the general circulation modeler. The semi-analytic theory greatly simplifies the problem of sub-grid scale parameterization of gravity waves in models. Such a treatment of gravity waves will be useful to the Air Force in its predictive capabilities for atmospheric flows, and the effects on Air Force missions and operations.

There do exist a few limitations of the theory, which now deserve more complete treatment so that a better theoretical understanding and broader practical application can be achieved. Briefly, these are as follows. First, the observed gravity waves are not always near-monochromatic, but sometimes

exist in multiple wave superposition. Convective turbulence is therefore expected to result from superposition, and affect all waves present. The required amplitudes for instability will be lower than those required for monochromatic wavebreaking, and the subsequent propagation of all waves will in turn be affected by the breaking. Hence, a slight generalization of the monochromatic semi-analytic theory is needed that takes into account the presence of multiple gravity waves acting in superposition. Second, the observed waves sometimes are three-dimensional in their structure, particularly when under the influence of the earth's rotation. As first noted by Dunkerton (1984), the dynamical breakdown of inertia-gravity waves occurs well before the onset of convective turbulence. Therefore it is now necessary to determine if a simple modification of the semi-analytic theory to include "dynamical saturation" due to KH instability is adequate to represent this breakdown. Third, the field of gravity waves in the middle atmosphere may interact with the quasi-two-dimensional turbulence of the horizontal flow. Local enhanced shears could excite radiating waves or elastically scatter ambient waves propagating vertically through the region. These effects, however, are poorly understood at present.

The effects of superposition, rotation, and two-dimensional turbulence are now being studied by the author, results of which will be reported elsewhere.

In conclusion, these new areas of research are important in the broader context of atmospheric observations of internal gravity waves. In particular, all of these issues of current theoretical interest clearly point to the need for networks of observing stations. Presently, all of our knowledge of high-frequency, fine-structured internal waves comes from single station

measurements, except for a few specialized programs that have taken place in recent years. Although the single station measurements are quite adequate for small horizontal scales--and indeed more of such observations are needed on a global scale--they are inadequate to discern how much energy and momentum flux is resident in the longer scales (several hundred to a few thousand kilometers horizontal wavelength). These waves are expected to propagate vertically on the basis of linear wave theory, and they are indeed inferred to exist on the basis of certain observations of inertia-gravity waves in the upper stratosphere.

Consequently there is a need for several organized networks of observing stations, by which cross-correlation studies can be performed in order to determine how much momentum is transported vertically by inertia-gravity waves of long horizontal scale. Until this gap in our understanding is filled, the knowledge of the internal gravity wave spectrum must be considered incomplete. Such waves will play an essential role in constructing global climatologies of the wave spectrum and their effect on the general circulation.

6. PROFESSIONAL PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

Part of this research was performed in collaboration with Dr. David C. Fritts, Geophysical Institute, University of Alaska.

## 7. INTERACTIONS

Dr. Dunkerton presented an invited review paper, "Our current understanding of gravity waves in the dynamics of the middle atmosphere," at the American Meteorological Society's Upper Atmosphere Meeting held in Boulder, Colorado, in April 1985. At that meeting, Dr. Dunkerton also presented a paper on "Breaking planetary waves in the mesosphere." In addition to these presentations, the author has given several seminars at the University of Washington, Princeton University, Iowa State University, the University of Illinois, and elsewhere, dealing with various aspects of planetary and gravity waves.

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